

THE USE OF TRACERS TO MONITOR THE CONDITION OF STORED MATERIALS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Application No. 63/596,614, filed on November 6, 2023. This application is incorporated by reference herein in its entirety for all purposes.

TECHNICAL FIELD

[0002] Articles, systems, and methods related to the monitoring of stored materials are generally described.

BACKGROUND

[0003] Degradable and/or condition sensitive and/or hazardous materials, such as biomass, food products, pharmaceuticals, medical products, food items, chemical products, radioactive materials and/or hazardous waste, are often stored in conditions to prevent degradation, damage, and/or leakage from containers or storage units. However, even when stored, the materials may be exposed to conditions in which they may degrade or otherwise be compromised and/or leak contents such that creating hazardous conditions or undesirable pollution or damage or loss of value of the stored materials. Accordingly, improved systems and methods for monitoring stored materials are useful and beneficial.

SUMMARY

[0004] Articles, systems, and methods related to the monitoring stored materials via the use of one or more tracers in a tracer composition are generally described. The subject matter of the present disclosure involves, in some cases, interrelated products, alternative solutions to a particular problem, and/or a plurality of different uses of one or more systems and/or articles.

[0005] In one aspect, methods are disclosed. In one embodiment, a method for monitoring for a leak in a materials storage facility, comprising including a frangible container containing one or more tracers in the materials storage facility to facilitate monitoring for the leak; and detecting the one or more tracers in the event of a release of the tracer from the frangible container is disclosed.

[0006] In another embodiment, a method for monitoring for a leak in a materials storage facility, comprising including one or more liquid and/or solid tracers in the materials storage facility; wherein the one or more tracers are selected to release one or more tracer

vapors and/or undergo a phase change to form one or more gaseous tracers; and detecting the one or more tracer vapors and/or gaseous tracers in the event of a release of the one or more tracer vapors and/or gaseous tracers within or from the materials storage facility is disclosed.

[0007] In another embodiment, a method for monitoring for a leak in a degradable material storage facility, comprising coating one or more tracers onto biomass within or for placement in the biomass storage facility; and detecting the one or more tracers in the event of a release of the one or more tracers from the coated biomass is disclosed.

[0008] In another embodiment, a method for determining a location of a leak in a materials storage facility, comprising detecting one or more tracers using a plurality of sensors; and determining a location of the leak based on a position of one or more sensors detecting the leak, and/or a concentration and/or composition of the one or more tracers detected is disclosed.

[0009] In another embodiment, method for monitoring for a leak in a biomass storage facility, comprising including one or more tracers in the biomass storage facility; wherein the one or more tracers are; or are included in, associated with, or released by; a composition able to reduce or maintain a concentration of water in biomass in the storage facility, reduce or maintain a partial pressure of oxygen in the biomass in the storage facility, and/or reduce a live bacterial content of the biomass in the biomass storage facility below that of a level of live bacteria initially contained in the biomass before exposure to the one or more tracers; and detecting the one or more tracers in the event of a release of the one or more from biomass stored in the storage facility is disclosed.

[0010] In another embodiment, a method for monitoring for a leak in a materials storage facility, comprising associating a composition comprising a mixture of tracers with a first container of the storage facility, wherein the storage facility comprises a plurality of containers; and detecting one or more tracers of the mixture of tracers in the event of a release of the tracers from the first container of the storage facility is disclosed.

[0011] In another embodiment, a method for monitoring for a leak in a storage facility, comprising covering biomass with an encapsulating layer, the encapsulating layer comprising one or more tracers; and detecting the one or more tracers in the event of a release of any tracer from the encapsulating layer is disclosed.

[0012] In another aspect, as series of articles are disclosed. In one embodiment, an article, comprising biomass for sequestration or storage in a biomass storage facility; and at least

two tracers associated with the article that are detectable by at least one sensor to indicate a leak, failure, or degradation of the article or the biomass indicative of an undesirable condition of storage or sequestration is disclosed.

[0013] In another embodiment, an article, comprising a quantity of a material for sequestration or storage in a materials storage facility; and one or more tracers that are; or are included in, associated with, or released by; a composition able to reduce or maintain a concentration of water in the quantity of the material in the materials storage facility, reduce or maintain a partial pressure of oxygen of the quantity of the material in the materials, and/or reduce a bacterial content of the quantity of the material in the materials storage facility below that of a level of live bacteria initially contained in the quantity of the material before exposure to the composition comprising the one or more tracers, wherein the one or more tracers are detectable by a sensor to indicate a leak, failure, or degradation of the article or biomass indicative of an undesirable condition of storage or sequestration is disclosed.

[0014] In another aspect, a materials storage facility, comprising at least one compartment; a gas sampling and analysis system configured to detect the presence and, optionally, concentration of at least two tracers within and/or released from the at least one compartment, wherein the at least one compartment contains a stored material and a mixture of at least two tracers is disclosed.

[0015] In another aspect, a computer readable medium storing instructions that, when executed by a computer, cause the computer to determine, from a measurement of an identity of a detected tracer and/or relative concentration of one or more tracers in a detected tracer mixture, a location and/or identity of a compromised and/or leaking compartment of a materials storage facility.

[0016] Other advantages and novel features of the present disclosure will become apparent from the following detailed description of various non-limiting embodiments of the disclosure when considered in conjunction with the accompanying figures. In cases where the present specification and a document incorporated by reference include conflicting and/or inconsistent disclosure, the present specification shall control.

[0017] Also provided herein are methods for monitoring for a leak in a materials storage facility, comprising: (i) placing a tracer in the materials storage facility, wherein the tracer reacts with water or oxygen to form a tracer vapor; and

[0018] (ii) detecting the tracer vapor.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] Non-limiting embodiments of the present disclosure will be described by way of example with reference to the accompanying figures, which are schematic and are not intended to be drawn to scale unless otherwise indicated. In the figures, each identical or nearly identical component illustrated is typically represented by a single numeral. For purposes of clarity, not every component is labeled in every figure, nor is every component of each embodiment of the disclosure shown where illustration is not necessary to allow those of ordinary skill in the art to understand the disclosure. In the figures:

[0020] FIG. 1 is a schematic diagram of a system for monitoring for tracers indicative of a leak or other compromised condition of stored materials in a materials storage facility, according to some embodiments;

[0021] FIGs. 2A – 2E illustrate exemplary processing steps for size reduction (FIG. 2A), sterilizing (FIG. 2B), consolidating (FIG. 2C), encapsulating (FIG. 2D, and long-term storage (FIG. 2E) of biomass as an example of a stored degradable material appropriate for monitoring via use of certain embodiments of methods and systems described herein; and

[0022] FIG. 3 shows a process flow diagram of an exemplary method for determining a location of leak or other compromised condition in a materials storage facility detected by the release and detection of one or more tracers, according to some embodiments.

DETAILED DESCRIPTION

Definitions

[0023] The indefinite articles “a” and “an,” as used herein in the specification and in the claims, unless clearly indicated to the contrary, should be understood to mean “at least one.”

[0024] The phrase “and/or,” as used herein in the specification and in the claims, should be understood to mean “either or both” of the elements so conjoined, i.e., elements that are conjunctively present in some cases and disjunctively present in other cases. Other elements may optionally be present other than the elements specifically identified by the “and/or” clause, whether related or unrelated to those elements specifically identified unless clearly indicated to the contrary. Thus, as a non-limiting example, a reference to “A and/or B,” when used in conjunction with open-ended language such as “comprising”

can refer, in one embodiment, to A without B (optionally including elements other than B); in another embodiment, to B without A (optionally including elements other than A); in yet another embodiment, to both A and B (optionally including other elements); etc.

[0025] As used herein in the specification and in the claims, “or” should be understood to have the same meaning as “and/or” as defined above. For example, when separating items in a list, “or” or “and/or” shall be interpreted as being inclusive, i.e., the inclusion of at least one, but also including more than one of a number or list of elements, and, optionally, additional unlisted items. Only terms clearly indicated to the contrary, such as “only one of” or “exactly one of,” or, when used in the claims, “consisting of,” will refer to the inclusion of exactly one element of a number or list of elements. In general, the term “or” as used herein shall only be interpreted as indicating exclusive alternatives (i.e., “one or the other but not both”) when preceded by terms of exclusivity, such as “either,” “one of,” “only one of,” or “exactly one of.” “Consisting essentially of,” when used in the claims, shall have its ordinary meaning as used in the field of patent law.

[0026] As used herein in the specification and in the claims, the phrase “at least one,” in reference to a list of one or more elements, should be understood to mean at least one element selected from any one or more of the elements in the list of elements, but not necessarily including at least one of each and every element specifically listed within the list of elements and not excluding any combinations of elements in the list of elements. This definition also allows that elements may optionally be present other than the elements specifically identified within the list of elements to which the phrase “at least one” refers, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, “at least one of A and B” (or, equivalently, “at least one of A or B,” or, equivalently “at least one of A and/or B”) can refer, in one embodiment, to at least one, optionally including more than one, A, with no B present (and optionally including elements other than B); in another embodiment, to at least one, optionally including more than one, B, with no A present (and optionally including elements other than A); in yet another embodiment, to at least one, optionally including more than one, A, and at least one, optionally including more than one, B (and optionally including other elements); etc.

[0027] As used herein, “wt.%” is an abbreviation of weight percentage. As used herein, “at%” is an abbreviation of atomic percentage.

[0028] Some embodiments may be embodied as a method, of which various examples have been described. The acts performed as part of the methods may be ordered in any

suitable way. Accordingly, embodiments may be constructed in which acts are performed in an order different than illustrated, which may include different (e.g., more or less) acts than those that are described, and/or that may involve performing some acts simultaneously, even though the acts are shown as being performed sequentially in the embodiments specifically described above.

[0029] Use of ordinal terms such as “first,” “second,” “third,” etc., in the claims to modify a claim element does not by itself connote any priority, precedence, or order of one claim element over another or the temporal order in which acts of a method are performed, but are used merely as labels to distinguish one claim element having a certain name from another element having a same name (but for use of the ordinal term) to distinguish the claim elements.

[0030] In the claims, as well as in the specification above, all transitional phrases such as “comprising,” “including,” “carrying,” “having,” “containing,” “involving,” “holding,” and the like are to be understood to be open-ended, i.e., to mean including but not limited to. Only the transitional phrases “consisting of” and “consisting essentially of” shall be closed or semi-closed transitional phrases, respectively, as set forth in the United States Patent Office Manual of Patent Examining Procedures, Section 2111.03.

[0031] The term “materials storage facility” refers to a site for storing a stored material. Stored materials are described throughout this disclosure. In embodiments, the materials storage facility is a landfill or a biolandfill. Biolandfills are described in the following patent documents, which are incorporated by reference herein in its entirety for all purposes: International Publication No. 2024/129452 and International Publication No. 2024/129470.

[0032] The term “encapsulating layer,” which is used interchangeably with “encapsulation layer” is a material used to encompass a stored material. In embodiments, an encapsulating layer is a polymer. Multiple encapsulating layers are described in the following patent documents, which are incorporated by reference herein in their entireties: International Publication No. 2024/129452, International Publication No. 2024/129470, and PCT/US2024/027523.

[0033] As used herein, the term “about” or “approximately” when preceding a numerical value indicates the value plus or minus a range of 10%. For example, “about 100” encompasses 90 and 110.

Materials Storage Facilities and Methods for Monitoring for Leaks in Materials Storage Facilities

[0034] Systems and methods for monitoring degradable and/or condition sensitive and/or hazardous materials, such as biomass, food products, pharmaceuticals, medical products, food items, chemical products, radioactive materials and/or hazardous waste are disclosed (all examples, when stored, of a “stored material” as used herein) . In some embodiments, the stored materials are stored in a materials storage facility. In some embodiments, one or more tracers may be included for monitoring the stored materials, as described below. In certain embodiments, the tracers are added to, incorporated in, or otherwise associated with, a stored material, and/or are added to or otherwise contained within and/or associated with a container or a compartment or storage unit within such compartment, containing the stored material in the materials storage facility. A variety of conditions or events may occur that may result in a dangerous or other compromised condition of the stored material, For example chemical and/or biological degradation of the material, for example upon exposure of the material to conditions in which the material may degrade, In other situations, storage compartments and/or containers or other containment modalities containing and/or encapsulating units of a stored material may become physically or otherwise disrupted or compromised to destroy or adversely impact their protective or barrier properties. Tracer(s) in such instances can be selected and incorporated in a manner to be released (e.g., from a breached or compromised compartment of the storage facility), after which the one or more tracers may be detected to provide information useful to an operator of such facility regarding the compromised condition. Certain embodiments use one or more tracers individually, while in these or other embodiments, combinations of tracers (e.g., two or more tracers present together in a mixture of tracers) are used to facilitate further information gathering, as described below. Also disclosed are related methods of using described systems and methods for detecting the one or more tracers for monitoring the stored materials.

[0035] Sensitive stored materials, such as biomass, food products, pharmaceuticals, and/or other degradable materials, and/or hazardous waste, are often stored in conditions to prevent degradation and/or release. However, even when stored, such materials may be exposed to conditions in which they may be compromised or degrade, which may cause such materials and/or degradation products thereof to subsequently be released from safe storage, e.g., pollute the environment, create a hazard, and/or cause a loss or damage to

the stored materials and/or the storage facility. Described are innovative systems and methods for using tracers to facilitate one or more of the following: detecting the presence of a leak or other compromised condition in a materials storage facility, identifying a location of such leak or compromised condition, and/or preventing further release of or damage to such stored materials.

[0036] Degradable materials are materials which may decompose, decay, and/or otherwise degrade over time. One degradable material of particular interest for long term storage for carbon sequestration is biomass. Other degradable materials may comprise food products, pharmaceuticals, biohazardous waste, and/or nuclear waste. In some cases, degradable materials may only undesirably degrade under certain conditions. For example, biomass may degrade in the presence of oxygen and/or water and/or microbes.

[0037] In some cases, it may be desirable to store degradable materials for extended periods without degradation for various reasons. For example, when the degradable material is biomass, the biomass may be advantageously stored in a biomass storage facility to sequester the carbon contained in the biomass. Storage of the carbon may be advantageous to remove carbon from the atmosphere on long time scales (e.g., at least 1 year, at least 10 years, at least 20 years, at least 50 years, etc.), e.g., which may be useful to mitigate climate change and be sold or traded as carbon credits. While the systems and methods disclosed herein are generally applicable to any sensitive, valuable, or hazardous stored material, for the purpose of exemplary description, certain discussion below focuses on degradable materials, and in particular biomass, as representative of stored materials generally.

[0038] As described herein, some of the systems and methods are related to monitoring for leaks in materials storage facilities to locate and rectify the leak and prevent the release and/or degradation of the degradable materials stored in the storage facility. For example, in some embodiments, the systems and methods described herein advantageously facilitate the monitoring of a degradable material to ensure that little to none of the degradable material may decompose, degrade, and/or escape (either itself and/or degradation and/or decomposition products thereof) from the materials storage facility. For biomass, the monitoring may help to achieve successful and long-term stable sequestration of carbon in the biomass. As noted above, while some degradable materials examples in the present application are described in the context of biomass for, for example for carbon sequestration, any other stored material (e.g., degradable material) may be monitored using

methods and systems disclosed herein or modifications thereof in place of biomass in a biomass storage facility.

[0039] In certain embodiments, one or more tracers are used to monitor the containment of the degradable material within the materials storage facility. Example tracers and methods of incorporating them into the stored materials and/or materials storage facility are described below. In some embodiments, the tracer may be a gaseous tracer (e.g., a tracer that is a gas at standard temperature and pressure “STP” or prevailing storage conditions if non-overlapping with STP) or a tracer vapor released by a material that is a liquid or solid at STP or prevailing storage conditions if non-overlapping with STP, so when a leak in the materials storage facility is present, the tracer may emanate (e.g., by mass transport) from the stored materials in the storage facility and be detected by one or more sensors. Referring again to the example of storing biomass, the monitoring of the biomass may ensure that the biomass that was initially stored is continuously maintained without degradation and associated production of greenhouse gases like carbon dioxide and methane that could be released from the storage facility thus subverting ability to validate the carbon sequestration and related carbon credits. Ensuring the stability of degradable material maintained within the materials storage facility may further ensure the safety and/or stability of surrounding materials, which may otherwise be exposed to the degradable materials and/or materials produced or released by the degradable causing such surrounding materials to leak or become degraded (e.g., of particular relevance for nuclear waste, reactive chemicals, and certain pharmaceuticals).

[0040] FIG. 1 illustrates a monitoring system 100 according to certain embodiments. System 100 comprises an overall storage compartment 105 (e.g., a compartment, a container, a room, etc.) of or in a materials storage facility containing units of degradable material 110 (e.g., briquettes of consolidated biomass, smaller containers filled with stored materials, etc.). Compartment 105 may be further sub-divided into sub-compartments or regions 131, 132, and 133, which may be, in certain cases, fluidically isolated, e.g., by a barrier represented by dotted lines 130. In other embodiments, no barriers or fluidically permeable barriers allow fluid communication among regions 131, 132, and 133. Each region 131, 132, 133 contains units 110 of degradable material containing one or more tracers, and in certain cases different mixtures of two or more of the one or more tracers. For example, as illustrated, the units 110, 110', 110'' of degradable material in region 131 comprise a first composition of one or more tracers, the units 110' of degradable material

in sub-compartment 132 comprise a second composition of one or more tracers, and the units 110'' of degradable material in sub-compartment 133 comprise a third composition of one or more tracers.

[0041] Advantageously, the presence of different compositions of one or more tracers within different regions or sub-compartments may be advantageous for detecting and/or identifying a location (e.g., which region/sub-compartment is leaking) of a leak within the materials storage facility. In other embodiments, depending on the number of sensors available, the number and size of stored units 110 and other factors, the resolution for providing different tracer compositions and the resulting resolution of leak localization may discriminate at the level of individual stored units 110, 110', 110''.

[0042] Referring again to FIG. 1, one of the units of degradable material 110 within region/compartment 131 is leaking a composition of one or more tracers 115. The sensor 120a, within the region/compartment 105 is configured to detect the one or more tracers 115. There may be multiple sensors positioned throughout the facility/system, as shown in FIG. 1 (i.e., sensors 120a, 120b, and 120c), which may help detect and/or identify a location of the leak in other regions/compartments/stored units in storage facility 100.

[0043] For example, in one case where partitions 130 are impermeable, the leak of one or more tracers 115 in sub compartment 131 may be identified by only sensor 120a. For a system without partitions 130 or with permeable partitions, the leak of one or more tracers 115 in sub-compartment 131 may be first and most strongly detected by sensor 120a, second by 120b, and third by 120c, due to the spatial relationships between the leak of one or more tracers and the particular sensor detecting.. Moreover, in certain embodiments, providing different compositions of the one or more tracers associated with the units of degradable material 110, 110', 110'' within each sub-compartment 131, 132, and 133, respectively, may further provide information about the location of the leak based on the tracer composition profile detected. Finally, in addition to the compositional information and the spatial information, depending on the sampling frequency of the sensors 120, additional temporal information about the evolution of the leak may be provided, which may help determine the location of multiple leaks that may occur at different times and/or in different regions/sub-compartments. As shown in FIG. 1, the information gathered by the sensors may be collected and processed by a computer 140 that is programmed with software, e.g., encoded on a computer readable medium, executed by the computer to identify the presence of and/or determine a location of a leak.

Exemplary Application – Monitoring Storage of Carbon Casted Biomass

[0044] FIG. 1 shows the monitoring of processed biomass material within a materials storage facility as exemplary of monitoring stored material, generally. In an exemplary application, the processed biomass is, prior to being positioned within the storage facility, subject to processing steps to stabilize the biomass for long-term stable carbon sequestration. For example, FIGS. 2A-2F shows a schematic diagram of a particularly advantageous carbon sequestration via biomass “carbon casting” technology involving, in the illustrated, exemplary embodiment, various processing steps for consolidating and stabilizing the biomass before storage and monitoring of the biomass. FIG. 2A shows unprocessed biomass 232 (logs and grass in the example illustrated) being comminuted, e.g., by grinding, chipping, pulverizing, etc., to form comminuted biomass 234.

[0045] In some cases, comminuting the biomass advantageously facilitates further processing (e.g., sterilizing, consolidating, encapsulating) of the biomass. For example, comminuting the biomass may increase the surface area to volume ratio of the biomass, allowing further processing steps (e.g., sterilizing) to be performed more effectively and/or efficiently. In addition, in some cases, comminuting may result in a flowable solid, which may facilitate consolidation of the biomass into a particular size and/or shape.

[0046] In some cases, the biomass to be comminuted may be unprocessed. In other cases, the biomass may have been processed via one or more other processing steps e.g., washing, sifting, cutting, etc. before being comminuted. According to some embodiments, the biomass may not need to be comminuted. For example, in some cases, a biomass like sawdust may be of a suitable size upon being received and may not need to be comminuted.

[0047] In some embodiments, comminuting the biomass comprises grinding, shredding, pounding, chopping, milling, and/or cutting the biomass. Comminuting the biomass may be performed using any suitable device. Non-limiting examples of suitable devices include grinders, shredders, hammer mills (e.g., as typically used during wood pelletization), chippers, flakers, refiners, and ball mills. Non-limiting examples of suitable shredders include Weima WL 4, WL 6, and WL 8 shredders. Those of ordinary skill and art will recognize various methods and devices for comminuting degradable material.

[0048] The comminuted biomass 234 may then be sterilized 240 as shown in FIG. 2B, e.g., by UV and/or IR radiation 242. In some cases, the comminuted biomass may be sterilized. In other cases, unprocessed degradable material may be sterilized before being comminuted. Sterilizing is to take its ordinary meaning in the art. Generally, sterilizing

indicates the at least partial removal, deactivation, and/or elimination of life, for example, microbes (e.g., methanogens, CO₂-producing microbes), within the biomass, thereby minimizing and/or preventing decomposition of the biomass by the microbes. In some cases, the degradable material may be encapsulated in one or more layers (e.g., one or more layers comprising a polymeric material) as described below before and/or after being sterilized, and the sterilization of the biomass may sufficiently reduce the number of microbes present such that decomposition of the biomass is slowed and/or halted within the one or more layers (e.g., one or more layers comprising a polymeric material).

[0049] In some embodiments, sterilizing the biomass may be performed using any of a variety of suitable methods, which will be understood by those of ordinary skill in the art. In some cases, sterilizing the biomass comprises heating the biomass and/or subjecting the biomass to UV or other sterilizing radiation. In certain cases, heating the biomass comprises exposing the degradable material to dry heat and/or wet heat (e.g., steam) using any suitable heating device. Non-limiting examples of suitable heating devices include ovens, autoclaves, water bath devices, water cascade devices, heat exchangers, dryers (e.g., rotary drum dryers, fluidized bed dryers, rolling bed dryers), convection furnaces, radiant heaters, and solar receivers.

[0050] In FIG. 2C, the comminuted biomass 234 may then be consolidated 250, e.g., by applying a force 252 to compress the biomass into, e.g., a briquette (or block) 254. While an isotropic force is shown in FIG. 2C, anisotropic forces for consolidating the comminuted biomass may also be used, depending on the desired final shape and properties of the consolidated biomass.

[0051] Consolidating the biomass, in some cases, may make the biomass easier to process (e.g., encapsulate), stack, transport, handle, store, and/or monitor. In certain embodiments, consolidating the biomass may advantageously result in units of consolidated biomass that can withstand relatively high compressive and/or shear loads and/or can resist rupture of one or more encapsulation layers. In some cases, the biomass being consolidated may be comminuted biomass and/or sterilized biomass. In some embodiments, consolidating the biomass may comprise applying pressure to at least a portion of the biomass such that the consolidated biomass has a higher density than the unconsolidated degradable material. In certain embodiments wherein the biomass comprises lignin, sufficient consolidating pressure may be applied to cause at least a portion of lignin of the biomass to crosslink.

[0052] Consolidating the degradable material may be performed using any suitable device. Non-limiting examples of suitable devices include extruders, presses (e.g., stamping presses, hydraulic presses, screw presses), and cuber machines. Those of ordinary skill and art will recognize various methods and devices for biomass.

[0053] The briquette 254 (which is an example of a unit of a stored material) may then be encapsulated by an encapsulation layer 262, (and/or inserted into a pre-formed container) as shown in FIGS. 2E-2F. In certain embodiments, the encapsulation later and/or container surrounding the briquette is impermeable or resistant to permeation of oxygen and/or water vapor to maintain sterility and prevent degradation of the biomass during long-term storage.

[0054] In some embodiments, processing the biomass comprises encapsulating the biomass in one or more layers (e.g., one or more layers comprising a polymeric material). In some embodiments, the one or more layers have a relatively low gas transmission rate of water vapor and/or oxygen. Accordingly, in certain cases, encapsulating the biomass in the one or more layers may advantageously reduce or eliminate formation of carbon-containing gases (e.g., CO₂, CH₄) by reducing or preventing introduction of microbes, water (e.g., liquid water, water vapor), and/or oxygen into the encapsulated biomass, thereby delaying, reducing, or eliminating biomass decomposition. In certain cases, encapsulating the biomass in the one or more layers may advantageously reduce or eliminate release of any carbon-containing gases (e.g., CO₂, CH₄) that are produced by decomposition of the encapsulated biomass due to the low gas transmission rate of the one or more layers. In addition, in some such cases wherein the biomass may begin to decompose and form CO₂ and/or CH₄, the low gas transmission rate of the one or more layers may lead to increased CO₂ and/or CH₄ levels in the encapsulated biomass, shifting the equilibrium of CO₂ and/or CH₄ production and thereby slowing the rate of decomposition and/or degradation.

[0055] Encapsulating, in accordance with some embodiments, may comprise surrounding the biomass with one or more layers (e.g., one or more layers comprising a polymeric material). In certain embodiments, encapsulating the biomass comprises coating, wrapping, shrink wrapping, spraying, brushing, dip-coating and/or otherwise depositing one or more layers (e.g., one or more layers comprising a polymeric material) on the consolidated biomass. In some embodiments, the one or more layers comprise a substantially conformal coating. In certain embodiments, the one or more layers comprise

one or more layers deposited (e.g., via wrapping, shrink wrapping, spraying, brushing, and/or dip-coating) on the consolidated biomass. In certain embodiments, the one or more layers comprise a pre-engineered envelope (e.g., a bag or container). In some instances, for example, the consolidated biomass may be inserted into a pre-engineered envelope (e.g., a bag or container). In certain instances, the pre-engineered envelope (e.g., bag or container) may comprise a polymeric material. In some embodiments, the one or more layers form a hermetic seal.

[0056] Encapsulating the biomass may be performed using any suitable device. Non-limiting examples of suitable devices include coating machines (e.g., spray-coating machines, dip-coating machines), wrapping machines, shrink wrapping machines, and automated bagging machines. Those of ordinary skill and art will recognize various methods and devices for encapsulating biomass.

Systems for monitoring tracers

[0057] The materials storage facility, according to some embodiments, may comprise one or more compartments for storing material. An example of a one such compartment 105 may be seen in FIG. 1. In each of the one or more compartments, there may be stored material therein. In some such embodiments, as described in more detail elsewhere herein, one or more tracers may be included, which may facilitate monitoring for a leak in or from the one or more compartments of the materials storage facility. In some embodiments, the materials storage facility comprises a plurality of one or more compartments, for example, at least 2 compartments, at least 5 compartments, at least 10 compartments, at least 15 compartments, at least 20 compartments.

[0058] There may be one or more sensors e.g., 120a, 120b, 120c in, or in fluid communication with, at least some, and preferably each of the one or more compartments of the materials storage facility. The one or more sensors may be configured to monitor for the presence of one or more tracers in each of the one or more compartments and/or configured to monitor for degradation products from stored degradable materials, e.g., CH₄ and/or CO₂ from biomass, as described elsewhere herein in more detail. In some embodiments, there may be a plurality of sensors present in each of the one or more compartments, which may have the same or different sensing capabilities.

[0059] In some embodiments, the materials storage facility comprises a plurality of compartments positioned throughout the facility. In some embodiments, each of the compartments may be independently and fluidically connectable to a ventilation system.

Fluidically connectable describes the relationship between the compartment and the ventilation system wherein fluid (e.g., a gas) may move between the compartment and the ventilation system in at least one orientation of the compartment and/or ventilation system. For example, in one set of embodiments, there may be a valve positioned between the compartment and/or the ventilation system. In some such embodiments, when the valve is open, fluid may flow between the ventilation system and the compartment, whereas when the valve is closed, fluid may not flow between the ventilation system and the compartment. While fluid only flows between the ventilation system and the compartment when the valve is open, in some embodiments, the ventilation system and the compartment are considered fluidically connectable because fluid may flow when the valve is open. Additionally, when the relationship between the compartment and the ventilation system allows for fluid to flow (e.g., when the valve is open in the preceding example), the compartment and the ventilation system are said to be in fluid communication.

[0060] In some embodiments, wherein each of the plurality of compartments are independently and fluidically connectable to a ventilation system, such a relationship may facilitate the monitoring of gases and vapors in the headspace of each compartment, for example, if there is a gas sampling and analysis system that is further in fluid communication with the ventilation system. A gas sampling and analysis system, in accordance with some embodiments, is configured to detect the presence and, optionally, concentration of one or more tracers within and/or released from the at least one compartment of the materials storage facility. In some such embodiments, the at least one compartment contains one or more stored units of a degradable material (e.g., one or more biomass briquettes 254) and one or more tracers. In some embodiments, the at least one compartment contains a stored material and at least two tracers. Identity of the one or more tracers, combinations of two or more tracers, and methods of adding tracers to the one or more compartments and/or stored materials units therein are described in more detail below.

[0061] In some embodiments, the sensors, ventilation system, when present, and sensing system is configured and arranged to allow for the independent analysis of gases and vapors present in each of the one or more compartments of the materials storage facility, which may permit the sensing system to pinpoint the location of a leak, e.g., if one or more tracers associated with a leak are detected in or from one or more of the compartments. That is, in some embodiments, one or more tracers may be released in or from one or more

compartments. In some such embodiments, as the gases/vapors from each compartment of the materials storage facility are tested, the presence of one or more tracers present in such gases/vapors would indicate the presence of a leak wherein one or more units of stored material is releasing the one or more tracer.

[0062] Provided herein are materials storage facilities comprising: (i) a tracer that reacts with water or oxygen to form a tracer vapor; (ii) a stored material; and (iii) a system for detecting the tracer vapor. In embodiments the system for detecting the tracer vapor comprises a spectrometer, an infrared sensor, an isotope analyzer, or a combination thereof. In embodiments, the tracer is present in a plurality of compartments positioned throughout the facility, and the system for detecting the tracer vapor comprises a computer programmed to determine the location of the tracer vapor. In embodiments, the stored material is a drug or medical product, biomass, a radioactive substance, a food product, or hazardous waste. In embodiments, the tracer and/or tracer vapor is isotopically labeled. In embodiments, the isotopic label is ^{13}C or ^{15}N . In embodiments, a container contains the tracer. In embodiments, the container is a frangible container. In embodiments, the frangible container is a glass vial, a blister-pack, or bubble wrap. In embodiments, the materials storage facility comprises from one to ten different tracers. In embodiments, the tracer is selected from one or more of acetic anhydride, phosphorous pentoxide, calcium carbide, formalin, chlorine dioxide, anhydrous hydrazine, anhydrous diethylhydroxylamine, glutaraldehyde, ethylene oxide, formaldehyde, and paracetic acid. In embodiments, the tracer comprises a protein, a lipid, a carbohydrate, or a combination thereof. In embodiments, the tracer comprises biomass from algae. In embodiments, the algae is from a genus selected from any one of *Alexandrium*, *Amphidinium*, *Anabaena*, *Ankistrodesmus*, *Asterionella*, *Botryococcus*, *Ceramium*, *Chaetoceros*, *Chlamydomonas*, *Chlorella*, *Corallina*, *Coscinodiscus*, *Cyclotella*, *Dunaliella*, *Ectocarpus*, *Fragilaria*, *Fucus*, *Gelidium*, *Gonyaulax*, *Gracilaria*, *Gymnodinium*, *Haematococcus*, *Karenia*, *Laminaria*, *Macrocystis*, *Microcystis*, *Nannochloropsis*, *Navicula*, *Noctiluca*, *Nostoc*, *Oedogonium*, *Oscillatoria*, *Palmaria*, *Phaeodactylum*, *Peridinium*, *Pinnularia*, *Porphyra*, *Prorocentrum*, *Prochlorococcus*, *Sargassum*, *Scenedesmus*, *Skeletonema*, *Spirulina*, *Spirogyra*, *Synechococcus*, *Tetraselmis*, *Thalassiosira*, *Ulva*, and *Volvox*.

[0063] In embodiments, the materials storage facility further comprises a liner and wherein the stored material is biomass that is contained in an encapsulating layer.

Tracers

[0064] While, as noted above, in certain embodiments— particularly when a stored material is a detectable material, such as a gas at STP, or a non-gas that produces detectable levels of a vapor at STP or other prevailing storage conditions if non-overlapping with STP, or a degradable material, such as biomass, that produces detectable gases or vapors upon degradation—sensors may be included in a sensing system that can detect the stored substance itself and/or degradation products thereof. But tracers, as that term is used herein, are substances that are not the stored substance itself or a degradation product thereof, but are rather added to or otherwise associated with the stored material to be readily detectable in the event of a leak, fault, and/or compromised condition. Tracers will preferably be stable for a sufficient period of time under anticipated storage conditions to permit the monitoring for their detection over such period of time to be indicative of a leakage or other storage failure condition. In certain embodiments, tracers are non-degradable or at least stable over a desired monitoring lifespan (e.g., over a period of time of at least a day, at least a week, at least a month, at least a year, at least 5 years, at least 10 years, at least 25 years, at least 50 years, at least 75 years, at least 100 years, or more). In certain embodiments, the tracer(s) may be non-degradable or at least stable over a time period at least as long as the anticipated storage time of the stored material with which they are used. A tracer(s) may be a substance (e.g., element, compound, mixture, single phase material, multi-phase material, composite, etc.) that is not the stored material itself or a degradation product of a stored degradable material, and which is detectable by a sensor or sensing system, such that detection of such tracer(s) can be used to indicate the release of the tracer (e.g., from a unit of stored material, storage compartment, region, etc. of or in a materials storage facility). In some embodiments, the release of the tracer(s) may indicate a leak, failure, or degradation of a stored unit of, compartment containing, etc. a stored material comprising the tracer(s) and/or may be indicative of an undesirable condition of storage or sequestration of a stored, e.g., degradable, material.

[0065] In some embodiments, the tracer may be a substance that is a gas at STP or other prevailing storage conditions if non-overlapping with STP. In other embodiments, as described further below, the tracer may be a non-gas phase material at STP or other prevailing storage conditions if non-overlapping with STP that produces a detectable vapor tracer at STP or other prevailing storage conditions if non-overlapping with STP. In some such embodiments, the tracer may be useful for monitoring leakage, encapsulation failure, container rupture, or other compromised condition very quickly after such event occurs.

When a stored material is biomass (or other degradable material), including tracers may allow for detection of conditions that would permit degradation prior to degradation commencing, giving an earlier warning of a problem than would detecting only a degradation product.

[0066] In some embodiments, mixtures of different tracers may be used to assist in determining a location within a biomass storage facility of a decomposing, leaking, or otherwise compromised unit of stored biomass or other stored materials, as described in more detail below.

[0067] In some embodiments, any tracer added to the stored material (e.g., biomass) may be added in a relatively small amount. In certain embodiments, any tracer added to the material may be present in an amount less than or equal to 1 wt.%, or less than or equal to 0.5 wt.%, or less than or equal to 1000 ppm, or less than or equal to 500 ppm, or less than or equal to 100 ppm, or less than or equal to 50 ppm, or less than or equal to 25 ppm, or less than or equal to 10 ppm, or less than or equal to 5 ppm, or less than or equal to 1 ppm. In certain embodiments, any tracer added to the material may be present in an amount in a range from 1 ppm to 1 wt.%, 10 ppm to 0.5 wt.%, 50 ppm to 1000 ppm, or 100 ppm to 500 ppm.

[0068] Non-limiting examples of potentially suitable tracers include sulfur hexafluoride, helium, hydrogen (H₂), mercaptans, acetic anhydride, phosphorus pentoxide, calcium carbide, xenon, formalin, and chlorine dioxide. The tracer may be in the form of a gas or a solid, liquid able to generate a detectable vapor at prevailing storage conditions.

[0069] The one or more tracers that are included in the materials storage facility, in accordance with some embodiments, may have further advantageous properties. For example, in some embodiments, the one or more tracers can reduce and/or maintain a concentration of water in a dry, degradable, or water-sensitive material. In some embodiments, the concentration of water in the degradable material which may benefit from the presence of the one or more such water-scavenging tracers may be less than or equal to 0.3 g_{water}/g_{biomass}, 0.2 g_{water}/g_{biomass}, 0.1 g_{water}/g_{biomass}, less than or equal to 0.05 g_{water}/g_{biomass}, less than or equal to 0.01 g_{water}/g_{biomass}, less than or equal to 0.005 g_{water}/g_{biomass}, or less than or equal to 0.001 g_{water}/g_{biomass}.

[0070] In some embodiments, the one or more tracers may reduce and/or maintain a concentration of oxygen in a degradable material or other oxygen sensitive in the storage facility. For example, in some cases, the concentration of oxygen in, or surrounding, or in

contact with the degradable or oxygen-sensitive material in the storage facility in the presence of the one or more tracers may be less than or equal to 3 wt.% to 5 wt.%—e.g., as may be typical for an oxygen-sensitive food—whereas for certain other more sensitive stored materials, such as oxygen sensitive chemicals or drugs, the concentration of oxygen in, or surrounding, or in contact with the degradable or oxygen-sensitive material in the storage facility in the presence of the one or more tracers may be in the 1–1000 ppm or even 1–1000 ppb or less range. In certain cases where a stored oxygen-sensitive material is encapsulated or sealed in a container, the partial pressure of oxygen in equilibrium with the stored material in the encapsulated unit or container in the presence of the one or more tracers is less than or equal to 20kPa, less than or equal to 10 kPa, less than or equal to 5 kPa, less than or equal to 2 kPa, or less than or equal to 1 kPa.

[0071] Non-limiting examples of potentially suitable water and/or oxygen reactive tracers include anhydrous hydrazine, which reacts with water to form hydrazine hydrate, and anhydrous diethylhydroxylamine (DEHA). These both also can act as oxygen scavengers under suitable conditions.

[0072] In embodiments, the tracer is selected from one or more of acetic anhydride, phosphorous pentoxide, calcium carbide, formalin, chlorine dioxide, anhydrous hydrazine, anhydrous diethylhydroxylamine, glutaraldehyde, ethylene oxide, formaldehyde, and paracetic acid. In embodiments, the tracer comprises a protein, a lipid, a carbohydrate, or a combination thereof. In embodiments, the tracer comprises biomass from algae. In embodiments, the algae is from a genus selected from any one of *Alexandrium*, *Amphidinium*, *Anabaena*, *Ankistrodesmus*, *Asterionella*, *Botryococcus*, *Ceramium*, *Chaetoceros*, *Chlamydomonas*, *Chlorella*, *Corallina*, *Coscinodiscus*, *Cyclotella*, *Dunaliella*, *Ectocarpus*, *Fragilaria*, *Fucus*, *Gelidium*, *Gonyaulax*, *Gracilaria*, *Gymnodinium*, *Haematococcus*, *Karenia*, *Laminaria*, *Macrocystis*, *Microcystis*, *Nannochloropsis*, *Navicula*, *Noctiluca*, *Nostoc*, *Oedogonium*, *Oscillatoria*, *Palmaria*, *Phaeodactylum*, *Peridinium*, *Pinnularia*, *Porphyra*, *Prorocentrum*, *Prochlorococcus*, *Sargassum*, *Scenedesmus*, *Skeletonema*, *Spirulina*, *Spirogyra*, *Synechococcus*, *Tetraselmis*, *Thalassiosira*, *Ulva*, and *Volvox*.

[0073] In accordance with some embodiments, the one or more tracers may be bactericidal and/or viricidal and reduce a live bacterial/viral content of the stored material in the material storage facility and/or maintain sterility and prevent bacterial and/or viral growth in a sterilized stored material. In some embodiments, an existing live bacterial/viral content

of the stored material in the material storage facility in the presence of the one or more tracers may be reduced by 1, 2, 3, 4, 5, 6 or more logs compared to the bacterial content initially present in the material before exposure to the one or more tracers. In certain embodiments where the stored material has been initially sterilized and/or is initially sterile, such one or more tracers may maintain sterility and prevent bacterial and/or viral growth such that an existing live bacterial/viral content of the stored material in the material storage facility in the presence of the one or more tracers may increase, over an anticipated time period of storage, by less than 6, 5, 4, 3, 2, 1 or less logs compared to the bacterial content initially present in the material before exposure to the one or more tracers. In some such embodiments, the tracer(s) may comprise, for example, formaldehyde, glutaraldehyde, ethylene oxide, chlorine dioxide, and/or paracetic acid.

[0074] In some embodiments, the tracer is contained in a frangible container, so that upon rupture of the frangible container in the event of a mechanical collapse or other disruption of a unit(s) of stored material containing or in contact with the frangible container, the tracer is released and detected. In certain embodiments, such a frangible container may be a glass vial, blister-pack, or bubble wrap, or other readily disruptable packaging containing the tracer(s).

[0075] In some embodiments, the tracer(s) comprises a compound that can be easily monitored (e.g., a gas that can be detected at a resolution of parts per billion or parts per trillion). In some embodiments, monitoring at least one property of the stored material comprises continuously or periodically measuring a tracer content in a storage facility, or in a storage compartment, regions of a storage compartment, stored material unit of or in such storage facility containing the stored material associated with the tracer(s). In certain cases, the ASTM-F2391 Standard Test Method for Measuring Package and Seal Integrity Using Helium as the Tracer Gas may be used as an exemplary detection or monitoring protocol. For example, in an embodiment involve storage units of a stored material in the form of polymer encapsulated consolidated biomass briquettes, such method can be used to evaluate the integrity of one or more encapsulation layers of one or more units of such material (e.g., briquettes and/or blocks of encapsulated biomass). In some embodiments, the tracer(s) are incorporated within the one or more units of stored material and/or within one or more container or encapsulation layers thereof, e.g., in a coating of one or more units (e.g., briquettes) of consolidated biomass.

[0076] In some embodiments, one or more (and, in some cases, all) units (e.g., briquettes and/or blocks of biomass) of a stored material may comprise or be functionally associated with one or more tracers. In certain embodiments, the tracer(s) may be incorporated into only a subset of units of stored material to provide a robust statistical sample (while maintaining high enough concentrations to facilitate detection in the event of a rupture or leak). In certain cases, different tracers may be used in different locations around a materials storage facility (e.g., biomass sequestration site) to provide a determination as to the location of a leak if one were to occur. In some cases, the tracer(s) may be inexpensive, stable, and/or non-reactive (chemically or biologically) with any stored materials to which that are added. In other cases, tracers, especially but not exclusively solid or liquid tracers or tracer precursors, may be reactive with water and/or oxygen to form one or more detectable gaseous tracers or vapor tracers (also called “tracer vapors”), which may enable determination of exposure of the stored material (e.g., biomass) to water or oxygen, or to generation of water or oxygen by or within stored degradable material, such as, biomass, e.g., as a result of decomposition or microbial activity. In some cases, the tracers may only need to be present in a stored material in low concentrations (e.g., ppm or ppb levels) for adequate detection sensitivity.

[0077] In some cases, wherein a stored degradable material comprises biomass, inclusion of stable carbon isotopes directly into the biomass may provide evidence that the biomass is decomposing and forming CO₂ and/or CH₄. Isotopic ratios of CO₂ and/or CH₄ could have the unique signal of the included isotope, and it could be determined what fraction of produced CO₂ and/or CH₄ was due to decomposition of sequestered biomass. In certain cases, stable carbon isotopes may be included in the carbon polymers of the one or more encapsulation layers.

[0078] In some cases, an isotopic signature may be determined for biomass of a particular origin (e.g., a profile of naturally occurring carbon isotopes in the biomass may be determined). In some cases, monitoring at least one property of the biomass may comprise monitoring any gas emissions from a sequestration site for the presence of the isotopic signature. In some such cases, detection of the isotopic signature may indicate decomposition of biomass from the particular origin. Isotopic labelling may also be used when monitoring other degradable materials, e.g., pharmaceuticals, food products, etc.

[0079] In some embodiments, there may be one or more tracers associated with an article comprising stored material. In some embodiments, the article comprises a unit of

degradable material, for example, as shown as elements 110, 110', and 110'' in FIG. 1, and the one or more tracers may be associated with each or some such units. As another example, the article may comprise a biomass unit for storage that has been processed as shown in FIGS. 2A-2E, and the one or more tracers may further be encapsulated with the biomass (e.g., or other degradable material) and/or may be present in the encapsulating layer. In some embodiments, mixtures of different tracers are used, e.g., mixtures of at least 2 tracers, at least 3 tracers, at least 4 tracers, at least 5 tracers, at least 6 tracers, at least 7 tracers, at least 8 tracers, or at least 9 tracers or more. In some embodiments, tracer mixtures having no more than 10 tracers, no more than 9 tracers, no more than 8 tracers, no more than 7 tracers, no more than 6 tracers, no more than 5 tracers, no more than 4 tracers, or no more than 3 tracers are used. Combinations of the foregoing ranges are possible. Other ranges are also possible. In some embodiments, there may be multiple units/articles of degradable material stored in the materials storage facility, e.g., as shown in FIG.1. In some such instances, one or more tracers may be associated with each individual unit. In some embodiments, a first set of the units may comprise a first tracer composition of one or more tracers that is different than a second tracer composition of one or more tracers associated with a second set of units. Various compositions of one or more tracers may be associated with different sets of stored units within a system.

[0080] In some embodiments, the materials storage facility may comprise one or more tracers as described above. In some embodiments, the materials storage facility comprises at least 2 tracers, at least 3 tracers, at least 4 tracers, at least 5 tracers, at least 6 tracers, at least 7 tracers, at least 8 tracers, or at least 9 tracers. In some embodiments, the materials storage facility comprises no more than 10 tracers, no more than 9 tracers, no more than 8 tracers, no more than 7 tracers, no more than 6 tracers, no more than 5 tracers, no more than 4 tracers, or no more than 3 tracers. Combinations of the foregoing ranges are possible. Other ranges are also possible.

[0081] The use of multiple tracers, e.g., at least 2 tracers, provides the ability to have higher resolution monitoring of the materials storage facility, according to some embodiments. For example, a single tracer, when released due to a leak or other degradation of an article comprising degradable material in a materials storage facility indicates the presence of a leak is occurring in the facility but does not provide any spatial information about the location of the leak. In contrast, when using compositions

comprising multiple tracers in different sets of articles within a storage facility, spatial information about the location of the leak may be gained.

[0082] For example, referring again to FIG. 1, the units of stored material (110, 110', 110'') may each individually be loaded with different combinations of one or more tracers, or, the different tracers may be partitioned such that all units within a region (131, 132, 133) of compartment 105 contain units with the same mix of one or more tracers, but the mixture of one or more tracers in each unit of the groups of units in each other region is different. Any such distribution at any level of resolution is possible, with the choice based on the number of unique tracers and tracer combinations available, the number and spatial distribution of stored units, the number of sensors available, etc., the spatial resolution desired/needed, and the tolerable cost and complexity of the monitoring system.

[0083] As a representative example, if a storage facility uses 2 tracers A and B, tracer A may be associated with the units 110 of stored material in region/sub compartment 131, tracer B may be associated with units 110' of stored material in region/sub-compartment 132, and a mixture of tracers A *and* B may be associated with units 110'' in region/sub compartment 133. Accordingly, depending on the identity and/or relative amounts of tracer(s) that is detected in the event of a leak, it may be determined if the leak is most likely occurring in sub compartment 131, 132, or 133. The level of resolution may be heightened by using larger numbers of tracers and more complex mixtures of multiple tracers and/or mixtures of tracers differing in the relative proportion of each tracer in the mixture. For instance, when 3 tracers are used, 7 combinations of tracers are possible (e.g., A, B, C, A+B, A+C, B+C, A+B+C), providing greater the resolution than of the instance with 2 tracers. The level of resolution correspondingly increases with the number of independent tracers.

[0084] Moreover, in addition to the composition (e.g., the identity of the tracers detected) the ratio of the tracer(s) may also provide information about the location of a leak. Referring again to the example wherein 2 tracers A and B are used, in some embodiments, a first set of units of stored material may be associated with both tracers A and B in a ratio of A:B of 9:1, wherein a second set of units of degradable material may be associated with both tracers A and B in a ratio A:B of 1:9. Accordingly, depending on the ratio of A:B detected by the one or more sensors present in the materials storage facility, the set of units of stored materials implicated may be further be narrowed. Note, that any such ratios may be used within the constraint of the sensors having sufficient resolving power to (1) detect

the presence of the tracers and to differentiate the concentrations of different tracer mixtures associated with different stored units/storage compartments. Exemplary mixture ratios of a first tracer to a second tracer, in some cases, include at least 1:1, at least 1:2, at least 1:5, at least 1:10, or at least 1:20. In some embodiments, the ratio may be no more than 1:50, no more than 1:20, no more than 1:10, no more than 1:5, or no more than 1:2. Combinations of the foregoing ranges are possible. Other ranges are also possible. Such ratios are also possible between a first tracer and a third tracer, a first tracer and a fourth tracer, and so forth, depending on the number of tracers present in the article.

[0085] It may be difficult to include one or more tracers with the degradable material when the tracer(s) are gaseous. Accordingly, it may be advantageous to include one or more tracers that are solid or liquid and that change phases to form a gaseous tracer (e.g., by boiling, evaporation, or sublimation) and/or produce a detectable vapor at STP and/or other conditions of storage, which may be detected upon a leak occurring within the materials storage facility. In some embodiments, the one or more tracers may be more feasibly (especially for gaseous tracers) included in the degradable material within a frangible container which may be configured to break, e.g., when handling the degradable material after including the frangible container and/or in response to some physical collapse/mechanical breach of the stored material sufficient to produce leakage or undesirable exposure. Accordingly, a quantified amount of the one or more tracers may be included within such frangible container. The quantified amount may comprise the one or more tracers in any phase within a frangible container, for example, as a solid, liquid, or gas.

[0086] The frangible container may be configured to be fractured, chipped, or otherwise broken to allow the escape of the one or more tracers contained in the frangible container within a unit of stored material. The frangible container may comprise a glass container. In some such embodiments, at least a portion of the glass container may comprise relatively thin glass that is susceptible to breaking when experiencing relatively small forces, such as a may be experienced when transporting a unit of degradable material comprising the frangible container containing one or more tracers. The frangible container may comprise any of a variety of suitable materials and forms (see above) as long as they are configured to break after being inserted into a unit of degradable material under suitably defined conditions.

[0087] In some embodiments, the tracer(s) or frangible container containing such tracer(s) may be included in a unit of stored material, for example, within an encapsulated briquette of biomass. In some embodiments, the tracer(s) or frangible container containing such tracer(s) may be included in a container containing one or more units of stored material, e.g., within compartment 105 as shown in FIG. 1. In some such embodiments, the one or more tracers may be released from a frangible container upon insertion of the frangible container in the compartment 105 – e.g., a weight of stacking the units is sufficient to rupture the frangible container. According to some embodiments, after inclusion of the frangible container, the frangible container may be broken to release the one or more tracers into the unit of degradable material or into a compartment containing one or more units of degradable material. In some embodiments, including the frangible container may comprise inserting the frangible container into a unit of degradable material and/or a compartment containing one or more units of degradable material.

[0088] As described elsewhere herein, in some embodiments, the tracer may comprise a substance in gaseous form that is detectable or that releases a vapor that is detectable, which detection thereby indicates a leak in the materials storage facility. In some embodiments, the one or more tracers are carried by, impregnated in, or otherwise liberated or released from a solid scaffold, e.g., a solid coated or impregnated with a liquid producing a tracer vapor. In some embodiments, the tracer comprising a solid or liquid may be selected to undergo a phase change to form one or more gaseous tracers when included in the materials storage facility. For example, in some embodiments, the tracer may be stored at a low temperature at which it is a solid or liquid prior to use in the materials storage facility; whereas such tracer when exposed to the conditions in a materials storage facility – e.g., a temperature that is higher than the low temperature at which the tracer(s) is stored, the tracer(s) may undergo a phase change to form a gaseous tracer or tracer vapor that is detectable to indicate a leak in the materials storage facility.

[0089] Changing a phase of the tracer(s) may comprise in some embodiments sublimating the tracer(s) gas or vapor. In some embodiments, changing a phase of the tracer(s) may comprise the tracer(s) melting and then boiling or evaporating to form gaseous tracer or tracer vapor that is detectable. The tracer(s) may be irradiated with radiation, in some embodiments, to facilitate a phase change of the tracer(s) to a gaseous tracer(s) and/or formation of a tracer vapor. According to some embodiments, the tracer(s) may be selected to react with a degradable material and/or other chemical that may be present (e.g., in the

atmosphere) such that the tracer(s) may form a gaseous or vapor tracer(s) upon such reaction caused by such exposure, thus indicating a breach of the stored material causing such exposure. In some such embodiments, the tracer(s) may comprise acetic anhydride, phosphorus pentoxide, and/or calcium carbide. Other methods of changing a phase of the tracer(s) are possible, as this disclosure is not so limited.

Monitoring/Detecting tracer(s)/determining a location of a leak.

[0090] In embodiments, provided herein are methods for monitoring a leak in a materials storage facility, comprising: (i) placing a tracer in the material storage facility, wherein the tracer reacts with water or oxygen to form a tracer vapor; and (ii) detecting the tracer vapor.

[0091] In some embodiments, the systems and methods may comprise monitoring for a leak of one or more tracers from a unit of degradable material and/or a compartment in the materials storage facility. In some embodiments, monitoring comprises directly or indirectly detecting the presence and/or measuring a concentration of one or more tracer(s). As described above, there may be one or more sensors present in the materials storage facility to facilitate monitoring for a leak of the one or more tracers from the degradable material in the materials storage facility, e.g., as shown as sensors 120 in system 100 in FIG. 1.

[0092] Detecting and using measurement of the identity and/or amount of the tracer(s) detected to determine a location of a leak or compromised stored unit(s) may proceed as shown in the example flow diagram of FIG. 3. Here, one or more tracers are detected using one or more sensors in a compartment of a materials storage facility in step 310. The one or more sensors identify an identity of the one or more tracers in step 312, which may provide spatial location of the leak as described above. Moreover, the one or more sensors may identify a concentration of the one or more tracer in step 314. As concentrations of the one or more tracers change at the outset of a leak, for example, due to the leak worsening and/or different mass transport of the one or more tracers (e.g., by diffusion) reaching different sensors at different times, which are subsequently detected at the one or more sensors, further information about the distance of each sensor from the leak in the facility may be gained. Furthermore, identifying the time at which the one or more tracers was detected at the one or more sensors in step 316 may further help to provide spatial resolution. As an example, in FIG. 1, sensor 120a is likely to be the first sensor to detect the one or more tracers from the leak 115 of the units 110 of stored material due to its proximity to the leak as compared to sensors 120b and 120c. Accordingly, in some

embodiments, the number and positioning of the sensors may further inform about a location of the leak. Again, referring to FIG. 3, steps 312, 314, and 316 may optionally be repeated. The information gathered by the one or more sensors by repeating these steps can provide further concentration change with time information that may help to better determine a location of a leak. The final determination of the origin/location of the leak can then be computed or determined in step 320 from the information gathered in the previous steps by, for example processor/controller/computer 140 of system 100.

[0093] In some cases, gas chromatography may be used to measure the composition of any gas emanating from or surrounding the stored material (e.g., gas that may be released due to the decomposition of degradable stored materials such as biomass, and/or one or more tracers as described above added to the stored material). In some cases, mass spectrometry may be used to determine the identity and/or amounts of different species in a gas sample to indicative of the presence of tracer(s), degradation products of stored materials, etc. In some cases, sensors 120a, 120b, and 120c comprise one or more such analytical instruments or are sample collectors that feed such instrument(s) via a ventilation system or other fluidic connection.

[0094] According to some embodiments, one or more such sensors may be placed at one or more locations within the materials storage facility (e.g., biomass sequestration site). In some instances, the one or more sensors may provide real-time data. In certain cases, the one or more sensors include one or more load cells (force sensors), which may be used to measure mass. In certain cases, the one or more sensors comprise or feed one or more chemical sensors configured to sense different molecules which may be indicative of tracer leakage and/or degradable material decomposition (e.g., biomass decomposition into CH₄, O₂, and/or isotopically labeled gases). In some cases, the sensors may comprise one or more ports placed at one or more locations within the sequestration site. In certain embodiments, the one or more ports may draw gases from the sequestration site, and the gases may be measured for the presence of one or more molecules (e.g., O₂, N₂, CO₂, CH₄,, tracer(s)) and/or moisture content. In some cases, the gases may be measured for the presence of one or more volatile organic compounds (VOCs). In some cases, the presence of one or more VOCs may indicate evolution or degradation of polymers within the sequestration site. In some embodiments, the gases that may be measured may be gaseous tracer(s) or tracer vapor(s).

[0095] As described above and in summary, monitoring for a leak in a materials storage facility, in some embodiments, may further facilitate determining a location of the leak. The location of a leak may be determined at least in part based on the position of one or more sensors in the materials storage facility, as shown in FIG. 1 as sensors 120a, 120b, and 120c in compartment/facility 105. For example, referring again to FIG. 3, which is a method flow diagram showing a method 300 for determining a location for a leak in the presence of one or more sensors. The method may comprise detecting one or more tracers at one or more sensors in a compartment of the materials storage facility 100. This may be done with standard analytical techniques, for example, gas chromatography and/or mass spectrometry. Following this, optional steps of identifying a composition of the one or more tracers (step 312), identifying a concentration of the one or more tracers at a specific time (Step 314), and identifying the time at which the one or more tracers was detected at the one or more tracers (Step 316) may be performed, and may optionally be repeated. These steps may lead to determining a location of a leak of the one or more tracers in the compartment of the materials storage facility.

[0096] In some embodiments, the system may comprise or methods may be implemented by a controller and/or computer 140, as shown in FIG. 1. In some embodiments, the controller may comprise a computer processor, and the processor can be used to control the sensors and/or any associated analytical instruments. In some embodiments, the method flow diagram of shown in FIG. 3 may be implemented using a controller to detect a leak and/or identify a location of leak from one or more units of stored material within a materials storage facility.

[0097] In embodiments, detection of a tracer or a tracer vapor is performed using an infrared gas sensor, a spectrometer, of a mass spectrometry machine.

[0098] In some embodiments, the methods described herein may be implemented using a controller(s) and/or computer implement control system(s). For example, as shown in FIG. 1, controller 140 comprises a computer that is associated with the sensors/instruments and that may perform the method steps shown in FIG. 3 for determining a location of a leak of a compartment and/or unit of degradable material.

[0099] The computer may be programmed to receive and analyze data from one or more sensors/instruments to detect the presence of one or more tracers associated with a leak of a unit of stored material and/or a compartment of the materials storage facility and then determine a location of the leak.

[0100] The controller(s) and/or computer implemented control system(s) can be part of or coupled in operative association with support device and/or other automated system components, and, in some embodiments, is configured and/or programmed to control and adjust operational parameters, as well as analyze and calculate values, for example pressure values, heights, TIP, etc. as described above. In some embodiments, the controller(s) and/or computer implemented control system(s) can send and receive reference signals to set and/or control operating parameters of the support device. In some embodiments, controller(s) and/or computer implemented control system(s) may be physically integrated into, physically connected to, or hard-wired with other components of a support device. In embodiments, controller(s) and/or computer implemented control system(s) can be separate from and/or remotely located with respect to the other system components and may be configured to receive data from one or more remote support devices of the disclosure via indirect and/or portable means, such as via portable electronic data storage devices, such as magnetic disks, or via communication over a computer network, such as the Internet or a local intranet.

[0101] The controller(s) and/or computer implemented control system(s) may include several known components and circuitry, including a processing unit (i.e., one or more processors), a memory system, input and output devices and interfaces (e.g., an interconnection mechanism), as well as other components, such as transport circuitry (e.g., one or more busses), a video and audio data input/output (I/O) subsystem, special-purpose hardware, as well as other components and circuitry, as described below in more detail. Further, controller(s) and/or computer implemented control system(s) may be a multi-processor computer system or may include multiple computers connected over a computer network.

[0102] The controller(s) and/or computer implemented control system(s) may include one or more processors, for example, a commercially available processor such as one of the series x86, Celeron and Pentium processors, available from Intel, similar devices from AMD and Cyrix, the 680X0 series microprocessors available from Motorola, and the PowerPC microprocessor from IBM. Many other processors are available, and the controller(s) and/or computer implemented control system(s) is not limited to a particular processor.

[0103] A processor typically executes a program called an operating system, of which WindowsNT, Windows95 or 98, Windows XP, Windows Vista, Windows 7, Windows 10,

UNIX, Linux, DOS, VMS, and MacOS and are examples, which controls the execution of other computer programs and provides scheduling, debugging, input/output control, accounting, compilation, storage assignment, data management and memory management, communication control and related services. The processor and operating system together define a computer platform for which application programs in high-level programming languages are written. The controller(s) and/or computer implemented control system(s) is not limited to a particular computer platform.

[0104] The controller(s) and/or computer implemented control system(s) may include a memory system, which typically includes a computer readable and writeable non-volatile recording medium, of which a magnetic disk, optical disk, a flash memory, and tape are examples. Such a recording medium may be removable, for example, a floppy disk, read/write CD, or memory stick, or may be permanent, for example, a hard drive.

[0105] Such a recording medium stores signals, typically in binary form (i.e., a form interpreted as a sequence of one and zeros). A disk (e.g., magnetic or optical) has several tracks, on which such signals may be stored, typically in binary form, i.e., a form interpreted as a sequence of ones and zeros. Such signals may define a software program, e.g., an application program, to be executed by the microprocessor, or information to be processed by the application program.

[0106] The memory system of controller(s) and/or computer implemented control system(s) also may include an integrated circuit memory element, which typically is a volatile, random access memory such as a dynamic random-access memory (DRAM) or static memory (SRAM). Typically, in operation, the processor causes programs and data to be read from the non-volatile recording medium into the integrated circuit memory element, which typically allows for faster access to the program instructions and data by the processor than does the non-volatile recording medium.

[0107] The processor generally manipulates the data within the integrated circuit memory element in accordance with the program instructions and then copies the manipulated data to the non-volatile recording medium after processing is completed. A variety of mechanisms are known for managing data movement between the non-volatile recording medium and the integrated circuit memory element, and the controller(s) and/or computer implemented control system(s) that implements the methods, steps, systems control, and system elements control described above is not limited thereto. The controller(s) and/or computer implemented control system(s) is not limited to a particular memory system.

[0108] At least part of such a memory system described above may store one or more data structures (e.g., look-up tables) or equations such as calibration curve equations. For example, at least part of the non-volatile recording medium may store at least part of a database that includes one or more of such data structures. Such a database may be any of a variety of types of databases, for example, a file system including one or more flat-file data structures where data is organized into data units separated by delimiters, a relational database where data is organized into data units stored in tables, an object-oriented database where data is organized into data units stored as objects, another type of database, or any combination thereof.

[0109] The controller(s) and/or computer implemented control system(s) may include a video and audio data I/O subsystem. An audio portion of the subsystem may include an analog-to-digital (A/D) converter, which receives analog audio information and converts it to digital information. The digital information may be compressed using known compression systems for storage on the hard disk to use at another time. A typical video portion of the I/O subsystem may include a video image compressor/decompressor of which many are known in the art. Such compressor/decompressors convert analog video information into compressed digital information, and vice-versa. The compressed digital information may be stored on hard disk for use at a later time.

[0110] The controller(s) and/or computer implemented control system(s) may include one or more output devices. Example output devices include a cathode ray tube (CRT) display, liquid crystal displays (LCD), light-emitting diode (LED) displays, and other video output devices, printers, communication devices such as a modem or network interface, storage devices such as disk or tape, and audio output devices such as a speaker.

[0111] The controller(s) and/or computer implemented control system(s) also may include one or more input devices. Example input devices include a keyboard, keypad, track ball, mouse, pen and tablet, communication devices such as described above, and data input devices such as audio and video capture devices and sensors. The controller(s) and/or computer implemented control system(s) is not limited to the particular input or output devices described.

[0112] It should be appreciated that one or more of any type of controller(s) and/or computer implemented control system(s) may be used to implement various embodiments described. Functions of the controller(s) and/or computer implemented control system(s) may be implemented in software, hardware or firmware, or any combination thereof. The

controller(s) and/or computer implemented control system(s) may include specially programmed, special purpose hardware, for example, an application-specific integrated circuit (ASIC). Such special-purpose hardware may be configured to implement one or more methods, steps, simulations, algorithms, systems control, and system elements control described above as part of the controller(s) and/or computer implemented control system(s) described above or as an independent component.

[0113] The controller(s) and/or computer implemented control system(s) and components thereof may be programmable using any of a variety of one or more suitable computer programming languages. Such languages may include procedural programming languages, for example, LabView, C, Pascal, Fortran, and BASIC, object-oriented languages, for example, C++, Java and Eiffel and other languages, such as a scripting language or even assembly language.

[0114] The methods, steps, simulations, algorithms, systems control, and system elements control may be implemented using any of a variety of suitable programming languages, including procedural programming languages, object-oriented programming languages, other languages, and combinations thereof, which may be executed by such a computer system. Such methods, steps, simulations, algorithms, systems control, and system elements control can be implemented as separate modules of a computer program or can be implemented individually as separate computer programs. Such modules and programs can be executed on separate computers.

[0115] Such methods, steps, simulations, algorithms, systems control, and system elements control, either individually or in combination, may be implemented as a computer program product tangibly embodied as computer-readable signals on a computer-readable medium, for example, a non-volatile recording medium, an integrated circuit memory element, or a combination thereof. For each such method, step, simulation, algorithm, system control, or system element control, such a computer program product may comprise computer-readable signals tangibly embodied on the computer-readable medium that define instructions, for example, as part of one or more programs, that, as a result of being executed by a computer, instruct the computer to perform the method, step, simulation, algorithm, system control, or system element control.

Examples

EXAMPLE 1

[0116] A tracer system is designed to monitor the integrity of an encapsulation layer and to connect any gas generation to biomass decomposition. The tracer is designed to react with water or oxygen to form a tracer vapor.

[0117] The tracer will be placed in a materials storage facility and the tracer vapor will be detected. Isotopically labeled ^{13}C tracers will be utilized. The following isotopically labeled tracers will be evaluated: glucose, sodium bicarbonate, cellulose, algal biomass, and algal protein. The tracers will be placed in a materials storage facility containing stored material (i.e., unlabeled rice hulls). $^{13}\text{CO}_2$ or $^{13}\text{CH}_4$ that would be the result of decomposition of any of the isotopically labeled materials will be detected using Picarro cavity ring down mass spectrometry.

[0118] A $^{13}\text{CO}_2$ or $^{13}\text{CH}_4$ signal will show degradation of the stored material.

[0119] While several embodiments of the present invention have been described and illustrated herein, those of ordinary skill in the art will readily envision a variety of other means and/or structures for performing the functions and/or obtaining the results and/or one or more of the advantages described herein, and each of such variations and/or modifications is deemed to be within the scope of the present invention. More generally, those skilled in the art will readily appreciate that all parameters, dimensions, materials, and configurations described herein are meant to be exemplary and that the actual parameters, dimensions, materials, and/or configurations will depend upon the specific application or applications for which the teaching of the present invention is/are used. Those skilled in the art will recognize, or be able to ascertain using no more than routine experimentation, many equivalents to the specific embodiments of the invention described herein. It is, therefore, to be understood that the foregoing embodiments are presented by way of example only and that, within the scope of the appended claims and equivalents thereto, the invention may be practiced otherwise than as specifically described and claimed. The present invention is directed to each individual feature, system, article, material, and/or method described herein. In addition, any combination of two or more such features, systems, articles, materials, and/or methods, if such features, systems, articles, materials, and/or methods are not mutually inconsistent, is included within the scope of the present invention.

INCORPORATION BY REFERENCE

[0120] All references, articles, publications, patents, patent publications, and patent applications cited herein are incorporated by reference in their entireties for all purposes. However, mention of any reference, article, publication, patent, patent publication, and patent application cited herein is not, and should not be taken as, an acknowledgment or any form of suggestion that they constitute valid prior art or form part of the common general knowledge in any country in the world. The following patent documents are incorporated by reference herein in their entireties for all purposes: International Publication No. 2024/129452; International Publication No. 2024/129470; and PCT/US2024/027523, filed May 2, 2024.

NUMBERED EMBODIMENTS OF THE DISCLOSURE

1. A method for monitoring for a leak in a materials storage facility, comprising:
including a frangible container containing one or more tracers in the materials storage facility to facilitate monitoring for the leak; and
detecting the one or more tracers in the event of a release of the tracer from the frangible container.
2. A method for monitoring for a leak in a materials storage facility, comprising:
including one or more liquid and/or solid tracers in the materials storage facility;
wherein the one or more tracers are selected to release one or more tracer vapors and/or undergo a phase change to form one or more gaseous tracers; and
detecting the one or more tracer vapors and/or gaseous tracers in the event of a release of the one or more tracer vapors and/or gaseous tracers within or from the materials storage facility.
3. A method for monitoring for a leak in a degradable material storage facility, comprising:
coating one or more tracers onto biomass within or for placement in the biomass storage facility; and
detecting the one or more tracers in the event of a release of the one or more tracers from the coated biomass.
4. A method for determining a location of a leak in a materials storage facility, comprising:
detecting one or more tracers using a plurality of sensors; and
determining a location of the leak based on a position of one or more sensors
detecting the leak, and/or a concentration and/or composition of the one or more tracers detected.
5. An article, comprising:
biomass for sequestration or storage in a biomass storage facility; and

at least two tracers associated with the article that are detectable by at least one sensor to indicate a leak, failure, or degradation of the article or the biomass indicative of an undesirable condition of storage or sequestration.

6. A method for monitoring for a leak in a biomass storage facility, comprising:
including one or more tracers in the biomass storage facility;
wherein the one or more tracers are; or are included in, associated with, or released by; a composition able to reduce or maintain a concentration of water in biomass in the storage facility, reduce or maintain a partial pressure of oxygen in the biomass in the storage facility, and/or reduce a live bacterial content of the biomass in the biomass storage facility below that of a level of live bacteria initially contained in the biomass before exposure to the one or more tracers; and
detecting the one or more tracers in the event of a release of the one or more from biomass stored in the storage facility.

7. An article, comprising:
a quantity of a material for sequestration or storage in a materials storage facility;
and one or more tracers that are; or are included in, associated with, or released by; a composition able to reduce or maintain a concentration of water in the quantity of the material in the materials storage facility, reduce or maintain a partial pressure of oxygen of the quantity of the material in the materials, and/or reduce a bacterial content of the quantity of the material in the materials storage facility below that of a level of live bacteria initially contained in the quantity of the material before exposure to the composition comprising the one or more tracers,
wherein the one or more tracers are detectable by a sensor to indicate a leak, failure, or degradation of the article or biomass indicative of an undesirable condition of storage or sequestration.

8. A method for monitoring for a leak in a materials storage facility, comprising:
associating a composition comprising a mixture of tracers with a first container of the storage facility, wherein the storage facility comprises a plurality of containers; and
detecting one or more tracers of the mixture of tracers in the event of a release of the tracers from the first container of the storage facility.

9. A method for monitoring for a leak in a storage facility, comprising:
covering biomass with an encapsulating layer, the encapsulating layer comprising:
one or more tracers; and
detecting the one or more tracers in the event of a release of any tracer from the encapsulating layer.
10. A materials storage facility, comprising:
at least one compartment;
a gas sampling and analysis system configured to detect the presence and, optionally, concentration of at least two tracers within and/or released from the at least one compartment,
wherein the at least one compartment contains a stored material and a mixture of at least two tracers.
11. The materials storage facility of embodiment 10, comprising a plurality of compartments positioned throughout the facility, wherein the gas sampling and analysis system comprises a computer programmed to determine a location and/or identity of a compromised and/or leaking compartment from an identity of a detected tracer and/or a relative concentration of one or more tracers in a detected tracer mixture.
12. A computer readable medium storing instructions that, when executed by a computer, cause the computer to determine, from a measurement of an identity of a detected tracer and/or relative concentration of one or more tracers in a detected tracer mixture, a location and/or identity of a compromised and/or leaking compartment of a materials storage facility.
13. The system of any one of the preceding system embodiments, wherein the storage facility comprises a biomass storage facility.
14. The system of any one of the preceding system embodiments, wherein the stored material comprises a degradable material.

15. The system or method of any one of the preceding embodiments, wherein the stored material comprises biomass.
16. The system or method of any one of the preceding embodiments, wherein the stored material comprises a food product.
17. The system or method of any one of the preceding embodiments, wherein the stored material comprises a drug or medical product.
18. The system or method of any one of the preceding embodiments, wherein the stored material comprises a chemical product.
19. The system or method of any one of the preceding embodiments, wherein the stored material comprises a hazardous waste.
20. The system or method of any one of the preceding embodiments, wherein the stored material comprises a radioactive material.
21. The method of any one of the preceding method embodiments, further comprising inserting a frangible container containing one or more tracers in the storage facility to facilitate monitoring for a leak.
22. The system or method of any one of the preceding embodiments, wherein the one or more tracers comprises xenon and/or chlorine dioxide.
23. The system or method of any one of the preceding embodiments, wherein the one or more tracers comprises formalin.
24. The method of any one of the preceding method embodiments, wherein changing the phase comprises melting and/or evaporating the one or more tracers.
25. The method of any one of the preceding method embodiments, wherein changing the phase comprises sublimating the one or more tracers.
26. The method of any one of the preceding method embodiments, wherein changing the phase is caused by irradiating the one or more tracers with radiation.

22. The system or method of any one of the preceding embodiments, wherein the one or more tracers comprises a solid scaffold impregnated with a liquid tracer.

23. The method of embodiment 15, further comprising coating one or more tracers onto biomass comprises including the tracer in a polymer encapsulating layer or external compartment containing the biomass.

24. The system of any one of the preceding embodiments, wherein releasing the one or more tracers from the biomass stored material comprises reacting the one or more tracers with water and/or oxygen to form one or more tracer vapors or gaseous tracers.

30. The system of any one of the preceding system embodiments, wherein the at least one compartment is a plurality of compartments.

31. The system of embodiment 30, wherein each compartment of the plurality of compartments is fluidically connected to the gas sampling and analysis system by a ventilation system.

32. The system or method of any one of the preceding embodiments, wherein the stored material is biomass and wherein the one or more tracers are able to reduce or maintain water in biomass to or at less than or equal to $0.3 \text{ g}_{\text{water}}/\text{g}_{\text{biomass}}$.

33. The system or method of any one of the preceding embodiments, wherein the stored material is biomass and wherein the one or more tracers are able to reduce or maintain an oxygen partial pressure in or in equilibrium with biomass to or at less than or equal to 20 kPa.

34. The system or method of any one of the preceding embodiments, wherein the one or more tracers are able to reduce live bacterial/viral content in the stored material so that in the presence of the one or more tracers live bacterial/viral content in the stored material is reduced by 1, 2, 3, 4, 5, 6 or more logs compared to the bacterial content initially present in the material before exposure to the one or more tracers in the stored material.

INCORPORATION BY REFERENCE

[0121] All references, articles, publications, patents, patent publications, and patent applications cited herein are incorporated by reference in their entireties for all purposes. However, mention of any reference, article, publication, patent, patent publication, and patent application cited herein is not, and should not be taken as, an acknowledgment or any form of suggestion that they constitute valid prior art or form part of the common general knowledge in any country in the world.

CLAIMS

What is claimed is:

1. A method for monitoring for a leak in a materials storage facility, comprising:
including a frangible container containing one or more tracers in the materials storage facility to facilitate monitoring for the leak; and
detecting the one or more tracers in the event of a release of the tracer from the frangible container.
2. A method for monitoring for a leak in a materials storage facility, comprising:
including one or more liquid and/or solid tracers in the materials storage facility;
wherein the one or more tracers are selected to release one or more tracer vapors and/or undergo a phase change to form one or more gaseous tracers; and
detecting the one or more tracer vapors and/or gaseous tracers in the event of a release of the one or more tracer vapors and/or gaseous tracers within or from the materials storage facility.
3. A method for monitoring for a leak in a degradable material storage facility, comprising:
coating one or more tracers onto biomass within or for placement in the biomass storage facility; and
detecting the one or more tracers in the event of a release of the one or more tracers from the coated biomass.
4. A method for determining a location of a leak in a materials storage facility, comprising:
detecting one or more tracers using a plurality of sensors; and
determining a location of the leak based on a position of one or more sensors detecting the leak, and/or a concentration and/or composition of the one or more tracers detected.
5. A method for monitoring for a leak in a biomass storage facility, comprising:
including one or more tracers in the biomass storage facility;
wherein the one or more tracers are; or are included in, associated with, or released by; a composition able to reduce or maintain a concentration of water in

biomass in the storage facility, reduce or maintain a partial pressure of oxygen in the biomass in the storage facility, and/or reduce a live bacterial content of the biomass in the biomass storage facility below that of a level of live bacteria initially contained in the biomass before exposure to the one or more tracers; and

detecting the one or more tracers in the event of a release of the one or more from biomass stored in the storage facility.

6. A method for monitoring for a leak in a materials storage facility, comprising:
associating a composition comprising a mixture of tracers with a first container of the storage facility, wherein the storage facility comprises a plurality of containers; and
detecting one or more tracers of the mixture of tracers in the event of a release of the tracers from the first container of the storage facility.

7. A method for monitoring for a leak in a storage facility, comprising:
covering biomass with an encapsulating layer, the encapsulating layer comprising:
one or more tracers; and
detecting the one or more tracers in the event of a release of any tracer from the encapsulating layer.

8. The method of any one of claims 1-7, wherein the tracers and/or tracer vapors are detected using an infrared gas sensor, a spectrometer, or a gas chromatography machine.

9. The method of any one of claims 1-8, wherein the tracer and/or the tracer vapor are isotopically labeled.

10. The method of claim 9, comprising detecting the isotopically labeled tracer vapor with an isotopically sensitive analyzer.

11. The method of claim 9 or 10, wherein the isotopic label is ^{13}C or ^{15}N .

12. The method of any one of claims 1-11, wherein a container comprises the tracer.

13. The method of claim 12, wherein the container is a frangible container.

14. The method of claim 13, wherein the frangible container is a glass vial, a blister-pack, or bubble wrap.
15. The method of any one of claims 1-14, comprising from one to ten different tracers.
16. The method of any one of claims 1-15, wherein the tracer is selected from one or more of acetic anhydride, phosphorous pentoxide, calcium carbide, formalin, chlorine dioxide, anhydrous hydrazine, anhydrous diethylhydroxylamine, glutaraldehyde, ethylene oxide, formaldehyde, and paracetic acid.
17. The method of any one of claims 1-16, wherein the tracer comprises a protein, a lipid, a carbohydrate, or a combination thereof.
18. The method of any one of claims 1-17, wherein the storage facility comprises biomass.
19. The method of claim 18, wherein the leak in the storage facility indicates decomposition of the biomass.
20. The method of any one of claims 1-19, wherein the storage facility comprises a drug or medical product.
21. The method of claim 20, wherein the leak in the storage facility indicates degradation of the drug or medical product.
22. The method of any one of claims 1-21, wherein the storage facility comprises a food product.
23. The method of claim 22, wherein the leak in the storage facility indicates decomposition of the food product.
24. The method of any one of claims 1-23, wherein the storage facility comprises a hazardous waste.

25. The method of any one of claims 1-24, wherein the materials storage facility comprises biomass encapsulated in an encapsulation layer, wherein the encapsulation layer comprises the tracer.
26. An article, comprising:
biomass for sequestration or storage in a biomass storage facility; and
at least two tracers associated with the article that are detectable by at least one sensor to indicate a leak, failure, or degradation of the article or the biomass indicative of an undesirable condition of storage or sequestration.
27. An article, comprising:
a quantity of a material for sequestration or storage in a materials storage facility;
and one or more tracers that are; or are included in, associated with, or released by; a composition able to reduce or maintain a concentration of water in the quantity of the material in the materials storage facility, reduce or maintain a partial pressure of oxygen of the quantity of the material in the materials, and/or reduce a bacterial content of the quantity of the material in the materials storage facility below that of a level of live bacteria initially contained in the quantity of the material before exposure to the composition comprising the one or more tracers,
wherein the one or more tracers are detectable by a sensor to indicate a leak, failure, or degradation of the article or biomass indicative of an undesirable condition of storage or sequestration.
28. The article of any one of claims 26-27, wherein the tracer is isotopically labeled.
29. The article of claim 28, wherein the isotopic label is ^{13}C or ^{15}N .
30. The article of any one of claims 26-29, comprising from one to ten different tracers.
31. The article of any one of claims 26-30, wherein the tracer is selected from one or more of acetic anhydride, phosphorous pentoxide, calcium carbide, formalin, chlorine dioxide, anhydrous hydrazine, anhydrous diethylhydroxylamine, glutaraldehyde, ethylene oxide, formaldehyde, and paracetic acid.

32. The article of any one of claims 26-31, wherein the tracer comprises a protein, a lipid, a carbohydrate, or a combination thereof.
33. A materials storage facility, comprising:
at least one compartment;
a gas sampling and analysis system configured to detect the presence and, optionally, concentration of at least two tracers within and/or released from the at least one compartment,
wherein the at least one compartment contains a stored material and a mixture of at least two tracers.
34. The materials storage facility of claim 33, wherein the tracer is isotopically labeled.
35. The materials storage facility of claim 34, wherein the isotopic label is ^{13}C or ^{15}N .
36. The materials storage facility of any one of claims 33-35, comprising from two to ten different tracers.
37. The materials storage facility of any one of claims 33-36, wherein the tracer is selected from one or more of acetic anhydride, phosphorous pentoxide, calcium carbide, formalin, chlorine dioxide, anhydrous hydrazine, anhydrous diethylhydroxylamine, glutaraldehyde, ethylene oxide, formaldehyde, and paracetic acid.
38. The materials storage facility of any one of claims 33-37, wherein the tracer comprises a protein, a lipid, a carbohydrate, or a combination thereof.
39. A method for monitoring for a leak in a materials storage facility, comprising:
(i) placing a tracer in the materials storage facility, wherein the tracer reacts with water or oxygen to form a tracer vapor; and
(ii) detecting the tracer vapor.
40. A method for monitoring for a leak in a materials storage facility, comprising detecting the presence of a tracer vapor produced when a tracer reacts with water or oxygen.

41. The method of claim 39 or 40, wherein the tracer vapor is detected using an infrared gas sensor, a spectrometer, or a gas chromatography machine.
42. The method of any one of claims 39-41, wherein the tracer and/or the tracer vapor is isotopically labeled.
43. The method of claim 42, comprising detecting the isotopically labeled tracer vapor with an isotopically sensitive analyzer.
44. The method of claim 42 or 43, wherein the isotopic label is ^{13}C or ^{15}N .
45. The method of any one of claims 39-44, wherein a container comprises the tracer.
46. The method of claim 45, wherein the container is a frangible container.
47. The method of claim 46, wherein the frangible container is a glass vial, a blister-pack, or bubble wrap.
48. The method of any one of claims 39-47, comprising from one to ten different tracers.
49. The method of any one of claims 39-48, wherein the tracer is selected from one or more of acetic anhydride, phosphorous pentoxide, calcium carbide, formalin, chlorine dioxide, anhydrous hydrazine, anhydrous diethylhydroxylamine, glutaraldehyde, ethylene oxide, formaldehyde, and paracetic acid.
50. The method of any one of claims 39-49, wherein the tracer comprises a protein, a lipid, a carbohydrate, or a combination thereof.
51. The method of any one of claims 39-50, wherein the materials storage facility comprises biomass.
52. The method of claim 51, wherein the leak in the materials storage facility indicates decomposition of the biomass.
53. The method of any one of claims 39-52, wherein the materials storage facility comprises a drug or medical product.

54. The method of claim 53, wherein the leak in the materials storage facility indicates degradation of the drug or medical product.
55. The method of any one of claims 39-54, wherein the materials storage facility comprises a food product.
56. The method of claim 55, wherein the leak in the materials storage facility indicates decomposition of the food product.
57. The method of any one of claims 39-56, wherein the materials storage facility comprises a hazardous waste.
58. The method of any one of claims 39-57, wherein the materials storage facility comprises biomass encapsulated in an encapsulation layer, wherein the encapsulation layer comprises the tracer.
59. A materials storage facility, comprising:
- (i) a tracer that reacts with water or oxygen to form a tracer vapor;
 - (ii) a stored material; and
 - (iii) a system for detecting the tracer vapor.
60. The materials storage facility of claim 59, wherein the system for detecting the tracer vapor comprises a spectrometer, an infrared sensor, an isotope analyzer, a gas chromatography machine, or a combination thereof.
61. The materials storage facility of claim 59 or 60, wherein the tracer is present in a plurality of compartments positioned throughout the facility, and wherein the system for detecting the tracer vapor comprises a computer programmed to determine the location of the tracer vapor.
62. The materials storage facility of any one of claims 59-61, wherein the stored material is a drug or medical product, biomass, a radioactive substance, a food product, or hazardous waste.

63. The materials storage facility of any one of claims 59-62, wherein the tracer and/or the tracer vapor is isotopically labeled.
64. The materials storage facility of claim 63, wherein the isotopic label is ^{13}C or ^{15}N .
65. The materials storage facility of any one of claims 59-64, wherein a container comprises the tracer.
66. The materials storage facility of claim 65, wherein the container is a frangible container.
67. The materials storage facility of claim 66, wherein the frangible container is a glass vial, a blister-pack, or bubble wrap.
68. The materials storage facility of any one of claims 59-67, comprising from one to ten different tracers.
69. The materials storage facility of any one of claims 59-68, wherein the tracer is selected from one or more of acetic anhydride, phosphorous pentoxide, calcium carbide, formalin, chlorine dioxide, anhydrous hydrazine, anhydrous diethylhydroxylamine, glutaraldehyde, ethylene oxide, formaldehyde, and paracetic acid.
70. The materials storage facility of any one of claims 59-69, wherein the tracer comprises a protein, a lipid, a carbohydrate, or a combination thereof.
71. The materials storage facility of any one of claims 59-70, wherein the materials storage facility further comprises:
- (iv) a liner; and
- wherein the stored material is biomass that is wrapped in an encapsulating layer.
72. The materials storage facility of claim 71, wherein the encapsulating layer comprises the tracer.
73. A computer readable medium storing instructions that, when executed by a computer, cause the computer to determine, from a measurement of an identity of a

detected tracer and/or relative concentration of one or more tracers in a detected tracer mixture, a location and/or identity of a compromised and/or leaking compartment of a materials storage facility.